Earth Surface Processes and Landforms
Earth Surf. Process. Landforms **24,** 481–502 (1999)

SLOPEWASH, SURFACE RUNOFF AND FINE-LITTER TRANSPORT IN FOREST AND LANDSLIDE SCARS IN HUMID-TROPICAL STEEPLANDS, LUQUILLO EXPERIMENTAL FOREST, PUERTO RICO

MATTHEW C. LARSEN*, ANGEL J. TORRES-SÁNCHEZ AND IRIS M. CONCEPCIÓN

US Geological Survey, GSA Center, 651 Federal Drive, Guaynabo, Puerto Rico, 00965, USA

Received 20 March 1998; Revised 22 September 1998; Accepted 30 September 1998

ABSTRACT

Rainfall, slopewash (the erosion of soil particles), surface runoff and fine-litter transport at humid-tropical steepland sites in the Luquillo Experimental Forest, Puerto Rico (18° 20' N, 65° 45' W) were measured from 1991 to 1995. Hillslopes underlain by (1) Cretaceous tuffaceous sandstone and siltstone in subtropical rain (tabonuco) forest with vegetation recovering from Hurricane Hugo (1989), and (2) Tertiary quartz diorite in subtropical lower montane wet (colorado and dwarf) forest with undisturbed forest canopy were compared to recent landslide scars. Monthly surface runoff on these very steep hillslopes (24° to 43°) was only 0·2 to 0·5 per cent of monthly rainfall. Slopewash was higher in sandy loam soils whose parent material is quartz diorite (averaging 46 g m^{-2} a^{-1}) than in silty clay loam soils derived from tuffaceous sandstone and siltstone where the average was 9 g m^{-2} a^{-1}. Annual slopewash of 100 to 349 g m^{-2} on the surfaces of two recent, small landslide scars was measured initially but slopewash decreased to only 3 to 4 g m^{-2} a^{-1} by the end of the study. The mean annual mass of fine litter (mainly leaves and twigs) transported downslope at the forested sites ranged from 5 to 8 g m^{-2} and was lower at the tabonuco forest site, where post-Hurricane Hugo recovery is still in progress. Mean annual fine-litter transport was 2·5 g m^{-2} on the two landslide scars. Copyright © 1999 John Wiley & Sons, Ltd.

KEY WORDS: slopewash; fine-litter transport; surface runoff; rainfall; steeplands; landslides; Luquillo Experimental Forest; Puerto Rico; humid tropics

INTRODUCTION

The erosion of soil particles by slopewash is considered important in seasonal and arid areas (Schumm, 1956; Temple and Rapp, 1972; Young and Saunders, 1986; Cerd and Garca-Fayos, 1997) but relatively little work on this topic has been published for the forested humid tropics (Ruxton, 1967; Birot, 1968; Williams, 1973; Zonneveld, 1975; Chatterjea, 1989, 1994; Goudie, 1995; see review in Reading *et al*., 1995). The dense, broadleaf–evergreen vegetation that characterizes the humid tropics was originally thought to minimize mechanical erosion of the soil surface (Krynine, 1936; Cailleux, 1959, cited in Zonneveld, 1975). Deep chemical weathering, the absence of mechanical weathering, and the 'almost complete absence of rainwash' typified the mountainous regions of the tropical rain forest according to Krynine (1936). In contrast, Ruxton (1967) observed that slopewash under mature primary rain forest in northern Papua was pronounced on steep hillslopes where leaf litter and duff were thin. Additionally, rapid rates of litter decomposition and canopy gaps are important factors enhancing slopewash, according to Birot (1968). Another factor described by Ruxton (1967) was the tendency for small raindrops in light rainfall to be retained in the forest canopy where they re-formed into waterdrops of large size. The constant fall of large drops, even when precipitation is from light rain, may explain why slopewash is an active process in the humid, montane forested tropics. According to Douglas (1967), however, slopewash in the tropics may be most important in areas where rainfall is seasonal and concentrated into high-intensity storms.

* Correspondence to: Dr M. Larsen, US Geological Survey, GSA Center, 651 Federal Drive, Guaynabo, Puerto Rico 00965–5703, USA. Email: mclarsen@usgs.gov

CCC 0197-9337/99/060481–22 $17.50

Bruenig (1975) measured average slopewash rates of 20 Mg km^{-2} a^{-1} under virgin forest, and data compiled in Unesco/UNEP/FAO (1978) indicate that slopewash may be as high as 100 Mg km^{-2} a^{-1} for the humid tropics in general (cited in Reading *et al.*, 1995). Working in Puerto Rico, Smith and Abrua (1955) determined that erosion varied strongly with increasing slope angle and agricultural practice. On steep slopes (37°), annual soil losses on grassed slopes were 200 Mg km^{-2} but were 1300 to 1600 Mg km^{-2} under sugar cane and sweet potatoes, respectively. Gellis *et al.* (in press) studied soil erosion in the Río Grande de Loíza basin, Puerto Rico, on 12 hillslope sites for a period of 22 months. Average annual yields varied with land-use type with low values of 10 Mg km^{-2} in secondary forest and pasture, 31 to 86 Mg km^{-2} on hillslopes in crops, and 288 to 910 Mg km^{-2} at construction sites.

This article presents the results of a four-year study of slopewash in the Luquillo Experimental Forest (LEF), Puerto Rico. The objective of the work was to estimate slopewash rates in relatively undisturbed watersheds in an environment – humid tropical steeplands – where little geomorphic research has been done. Several questions were posed: What is the relation between rainfall and surface runoff? What are slopewash rates on forested hillslopes and how do they relate to rainfall and surface runoff? Does the transport of fine litter correlate with slopewash? How do these processes vary on hillslopes that have been disturbed by landsliding, which is the dominant erosional process in this environment (Larsen and Simon, 1993; Larsen, 1997; Larsen and Parks, 1997)? Finally, what is the approximate contribution of slopewash to fluvial sediment yield measured in the LEF?

STUDY AREA

The island of Puerto Rico is situated at the eastern end of the Greater Antilles, 1700 km southeast of Miami, Florida, and is located in the path of the easterly tradewinds (Figure 1). The study area consists of several hillslopes and landslide scars overlying the two principal bedrock types in the 113 km^2 LEF, eastern Puerto Rico (Figure 1). The climate of the LEF is humid tropical, with a wet season of May to December although about 5 to 10 per cent of annual rainfall normally occurs each month (Brown *et al.*, 1983). Mean annual temperature at the study sites averages 21°C and mean monthly temperature varies little through the year (Calvesbert, 1970). Runoff varies with elevation and is as much as 82 per cent of precipitation in high-elevation watersheds (*c.* 900 m) but only 52 per cent of precipitation at lower-elevation watersheds (*c.* 400 m) (García-Martino *et al.*, 1996; Larsen and Concepción, 1998). Annual precipitation ranges from 3500 mm at 200 to 300 m elevation to as much as 5000 mm at $\geqslant$ 600 m elevation due to orographic effects (Brown *et al.*, 1983). More than 1600 rain showers per year were recorded at one site in the LEF (Odum *et al.*, 1970), and approximately 78 per cent of these showers were of 1 hour or less duration (Colón, 1983). Storms of high intensity (10 to 100 mm a^{-1}) are usually recorded in all months except for February and March. The principal weather systems affecting climate in the LEF are mesoscale atmospheric disturbances (easterly waves, cold fronts, tropical storms) and local convective storms (Odum *et al.,* 1970). Hurricanes are common in the Caribbean region during the months of August, September and October and normally pass over the Antilles islands before recurving northward under the influence of mid-latitude westerlies. Hurricanes have directly crossed the LEF about once every 60 years during the past several hundred years (Scatena and Larsen, 1991).

The Luquillo mountains, in which the LEF is located, are characterized by rugged topography and a maximum elevation of 1074 m above sea level. The steep slopes are highly dissected by perennial and ephemeral streams, and mean slope ranges from 0·222 (12·5°) in areas underlain by quartz diorite, to 0·365 (20·0°) in areas underlain by Cretaceous tuffaceous sandstone and siltstone. Deforestation for intensive subsistence and plantation agriculture was widespread in Puerto Rico during the 19th and early 20th century (Wadsworth, 1950; Birdsey and Weaver, 1987). Because of a combination of limited access resulting from steep slopes, high annual rainfall and conservation policies implemented by the Spanish crown early in the 19th century, most of the LEF was not subjected to forest clearing. In 1903, under US sovereignty, the Luquillo Forest Reserve was proclaimed and the area is now under the administration of the US Forest Service.

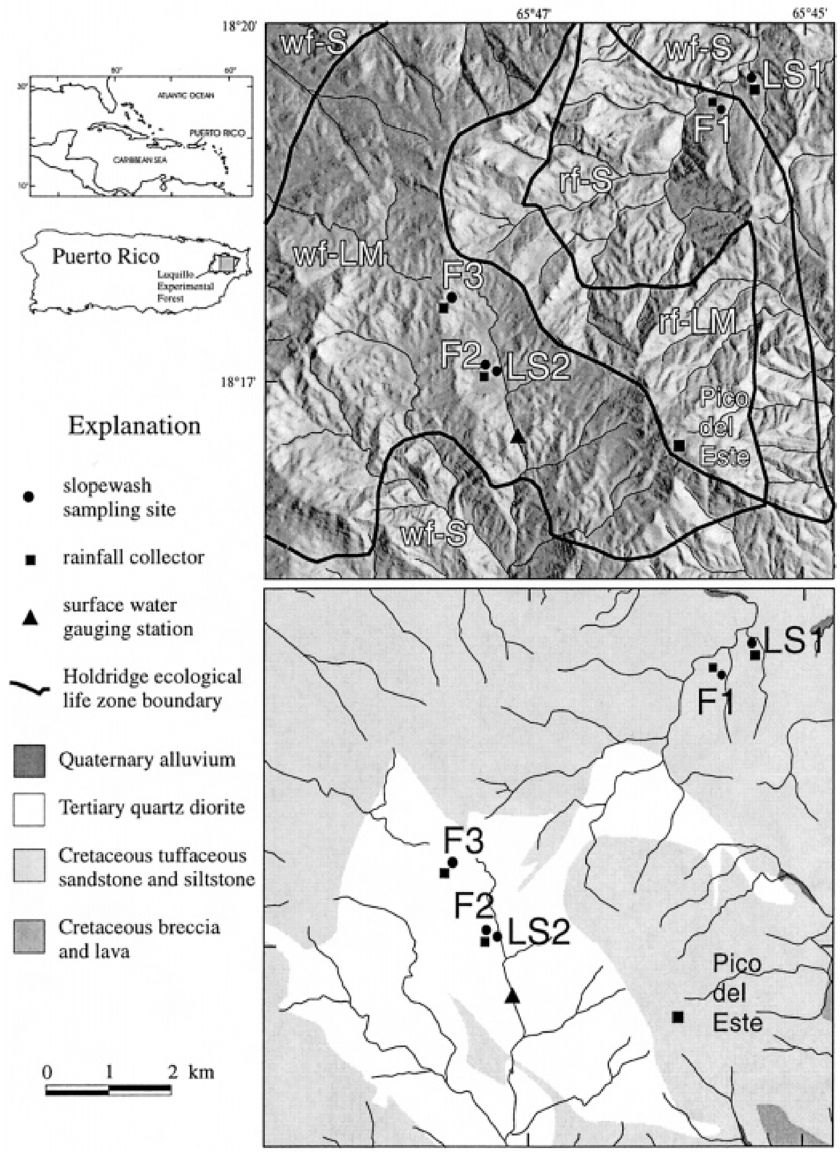

Figure 1. Maps showing location of study areas, streams, shaded relief, bedrock geology (simplified from Briggs and Aguilar-Cortés, 1980; Seiders, 1971) and Holdridge ecological life zones (Ewel and Whitmore, 1973) in the Luquillo Experimental Forest, eastern Puerto Rico. LS = landslide site; F = forested site; wf-S = subtropical wet forest; wf-LM = subtropical lower montane wet forest; rf-S = Subtropical rain forest; rf-LM = subtropical lower montane rain forest.

Forest structure and dynamics are dominated by disturbance regimes ranging in size and effect from individual treefall gaps, to landslides and hurricanes (Guariguata, 1990; Lugo and Scatena, 1995; Walker *et al*., 1996; Myster *et al*., 1997). Hurricanes are thought to be a major control of the forest ecology (Walker *et al*., 1991; Waide and Lugo, 1992). Larsen and Torres-Sánchez (1992), using data from a 1989 hurricane (Hugo), reported that rainfall-triggered landslides may disturb as much as 1·1 per cent of the forested hillslope area each century. The LEF treefall-gap turnover rate is 100 per cent per 135 years on average (Lugo and Scatena, 1995; Scatena and Lugo, 1995).

Most of the LEF is underlain by Lower Cretaceous tuffaceous andesitic grey and green sandstone and siltstone (Figure 1; Seiders, 1971; Briggs and Aguilar-Cortés, 1980). Tertiary-age quartz diorite

outcrops in an area of approximately 24 km^2. The quartz diorite is light grey, medium- to coarse-grained, and contains about 56 per cent plagioclase, 26 per cent quartz, 7 per cent hornblende, 5 per cent orthoclase, and 4 per cent biotite (Seiders, 1971). The silty clay loam to sandy loam soils overlying these rock types are Ultisols, typical of the upland areas of Puerto Rico (Boccheciamp, 1977). These soils have abundant clay- and silt-sized material but because the clay is well aggregated in the upper horizons, permeability is higher than might otherwise be expected (Jordan, 1970). The soil permeability is as high as 5 cm h^{-1} which is considerably greater than average rainfall intensity. Simon *et al.* (1990) report that shallow soils derived from quartz diorite have lower median cohesive strength (5·37 kPa, $n = 14$) than shallow soils developed from the tuffaceous sandstone and siltstone (7.79 kPa, $n = 14$). Soil augering on hillslopes and ridgetops commonly reveals a very narrow zone (several centimeters) at the boundary between completely weathered saprolite and fresh unweathered bedrock at depths of 2 to 10 m.

Puerto Rico and the nearby Virgin Islands contain a wide range of rock types associated with purely oceanic island arcs (Donnelly, 1989). The volcaniclastic and intrusive lithologies present in the study areas are typical of these oceanic island arcs. Furthermore, Ultisols represent 8·5 per cent of the world's soils (Foth, 1984). For these reasons, the study areas provide insights that can be applied to regions other than Puerto Rico.

METHODS

A total of 21 unbounded plots on several steep hillslopes under forest canopy and on recently exposed landslide scars were instrumented with Gerlach troughs and litter traps for sampling of slopewash, surface runoff and fine litterfall during the period between December 1991 and September 1995 (Table I). A Gerlach trough is a sediment trap designed to retain soil particles and surface runoff transported downslope by gravity (Young, 1960; Gerlach, 1967; Lewis, 1981; 1985; Sirvent *et al.*, 1997). The plots were grouped in five sets – three under forest canopy and two on recent landslide scars (Figure 1). The landslide scars had small surface areas (*c.* tens of square metres), and were bounded by forest. Sites F1 and LS1 were located on hillslopes overlying Cretaceous tuffaceous sandstone and siltstone in tabonuco (*Dacryodes excelsa*) forest classified as subtropical wet forest and subtropical rain forest (Figure 1; Ewel and Whitmore, 1973). The F2, F3 and LS2 sites were located on hillslopes overlying Tertiary quartz diorite in subtropical lower montane wet forest (Table I). The F2 and F3 sites are further classified as colorado (*Cyrilla racemiflora*) and dwarf forest, respectively (Waide and Lugo, 1992). Individual plots at each site were located within 5 to 20 m of each other on contiguous hillslope segments. Sampling was discontinued at the F3 site in 1993, at the F1 and LS1 sites at the end of 1994, and at the F2 and LS2 sites in September 1995. Because the F3 site was remote it was only sampled for a short period. Runoff and slopewash data collected at that site are therefore discussed only briefly.

A single 0·25 m^2 wire mesh litterfall collection trap was located next to each Gerlach trough at the forested sites. Only one litterfall collection trap was installed at the landslide scar sites. On average, the Gerlach troughs and leaf litter traps were sampled on a four-week cycle. At the same time, rainfall was measured in canopy gaps at sites F1 and F2. This was accomplished with two collectors that were constructed with a 9 cm diameter funnel that drained into a 4 litre bottle mounted on a 1 m high post.

The Gerlach troughs were fabricated with a plastic section of household rain gutter 50 cm in length with a hinged metal lid to prevent direct interception of rainfall and rainsplash-transported sediment (Lewis, 1985; Fitzhugh, 1992). A rectangular metal strip was attached to the upslope side of the trough and imbedded into the soil to allow slopewash, surface runoff and fine litter to enter the trough. A 13 mm diameter plastic tube connected the side of the trough to one or two 20 litre closed buckets anchored downslope to allow excess surface runoff water to be trapped. Regular sampling of each trap included scooping out sediment and fine litter caught in the trough, measuring the volume of water in the buckets, and subsampling fine sediment that had been transported into the buckets. Sediment subsampling was

Table I. Topographic and soil characteristics, and sampling period at Gerlach-trough sites in the Luquillo Experimental Forest, Puerto Rico. Soil density, moisture percentage and texture were determined from samples collected at the outset of the study at $\leqslant 5$ cm depth. Single values determined at site LS1 because of proximity of troughs. See Figure 1 for site locations

	F1											F2						F3		LS1	LS2	
Trough	1	2	3	4	5	6	7	8	9	10	Mean	1	2	3	4	5	Mean	1	2	1, 2	1	2
Moisture (%)	55	100	77	97	78	83	91	91	88	92	85	51	108	65	67	58	70	nd	nd	40	23	23
Dry bulk density (g cm^{-3}	0·75	0·69	0·65	0·67	0·84	0·86	0·78	0·77	0·80	0·70	0·75	1·08	0·65	0·86	0·83	1·00	0·88	0·61	0·62	1·3	1·52	1·56
Slope angle (degrees)	39	36	35	29	44	40	40	37	24	24	35	43	43	43	38	40	41	35	34	43	51	32
Slope aspect (degrees)	266	293	300	288	290	290	305	294	286	290	290	191	140	185	96	104	143	15	11	300	nd	nd
Sand (%)	27	16	15	13	24	54	28	20	14	27	24	67	52	60	66	64	62	67	61	nd	77	70
Silt (%)	32	43	36	40	35	21	31	35	37	31	34	22	30	22	18	17	22	14	17	nd	6	10
Clay (%)	41	41	48	47	41	25	41	45	49	42	42	11	18	18	16	19	16	19	22	nd	17	20
Drainage area (m^2)	9	16	14	13	11	16	15	12	30	12	15	35	16	5	14	14	17	42	18	14	19	19
Collection period (days)	1002	1002	1002	1197	1197	974	574	1169	574	574	927	1360	1360	1360	1360	1360	1360	457	457	993	516	1360
Bedrock	Cretaceous tuffaceous sandstone and siltstone											Tertiary quartz diorite						T. qtz diorite		Css	T. qtz diorite	
Forest type	*Dacryodes excelsa* (tabonuco)											*Cyrilla racemiflora* (colorado)						dwarf		na	na	

Css = Cretaceous sandstone and siltstone; T. qtz diorite = Teritiary quartz diorite; nd = no data; na = not applicable

accomplished by mixing sediment that had settled to the bottom of the bucket into a homogeneous slurry and then taking a depth-integrated sample of the slurry by lowering a 250 ml sample bottle horizontally through the bucket.

Laboratory analysis of the material retained in the Gerlach troughs included drying of soil and organic material for 24 h at 105°C, weighing to determine sediment and organic material mass, followed by ashing at 550°C for 1 h and reweighing to determine loss on ignition (LOI). In addition, the 250 ml water–sediment mixture was weighed, evaporated for 24 h at 105°C, and reweighed to determine sediment concentration. This concentration was then used with the total amount of water trapped in the buckets to estimate the additional amount of sediment that passed the troughs and entered the buckets. This portion was not ashed as it was composed entirely of fine sediment. Most of the LOI portion of material retained in the Gerlach troughs was composed of leaves and twigs and is an approximation of the mass of fine litter transported downslope. A small portion of LOI can be attributed to the additional moisture loss caused by ashing of samples at 550°C.

Fine leaf litter (leaves, twigs, flowers, fruit) trapped in the collection baskets adjacent to each Gerlach trough was placed in paper bags in the field. These were oven dried for 24 h at 105°C and weighed to determine their mass.

Soil characteristics were determined using standard techniques to analyse samples collected at the outset of the study at $\leqslant 5$ cm depth (Lambe, 1951). Moisture percentage was determined gravimetrically. Bulk density was determined by driving a 100 cm^3 aluminium cylinder into the soil and weighing the soil within after drying for 24 h at 105°C. Percentage sand, silt and clay was determined by hydrometer analysis. Although the determination of surface infiltration was not part of this study, data from two measurements made in a later investigation are included (Stonestrom *et al.,* 1998). These measurements were made with a ring infiltrometer (ASTM, 1988).

Data treatment

Raw slopewash, surface runoff and rainfall data from individual dates for each Gerlach trough were published by Larsen (1997). The collection schedule for surface runoff, slopewash and leaf-litter samples was irregular, ranging from 7 to 78 days. The mean collection frequency was 27 days with a standard deviation of 15 days. Because time series of data are most simply expressed with a regular time step or rate, the data presented herein are expressed as monthly rates. This was done by calculating the daily rate for each sample type and collection date and multiplying by 30·44, or 365·25/12.

Data limitations

Gerlach troughs provide an inexpensive means for quantifying surface runoff and slopewash but some problems typically occur. The use of unbounded plots for Gerlach troughs eliminates potential problems of enhanced surface runoff and scour at plot boundaries, but creates uncertainty in the determination of trough contributing area. The contributing drainage area for each Gerlach trough was estimated in the field and measured with a metric tape. These areas may vary plus or minus by as much as a factor of two because the forested terrain had variable microtopography. Regardless of whether bounded or unbounded plots are used, the contributing area for each trough is controlled by such factors as the intensity of a rainstorm, antecedent soil moisture, and the subsequent surface runoff. The surficial soil character within Gerlach trough contributing areas was extremely heterogeneous with patches of bare soil interspersed with litter-covered areas underlain by thick root mats. The rate of infiltration across this range of soil surfaces was observed to vary considerably. The collectors into which surface runoff was retained were occasionally overwhelmed by a large volume (in excess of 44 litres) resulting in underestimation of runoff. This occurred on less than 10 per cent of the sample collection dates. Other problems encountered were occasional decoupling of the Gerlach troughs from the soil and diversion of slopewash and runoff by the fall of large tree branches.

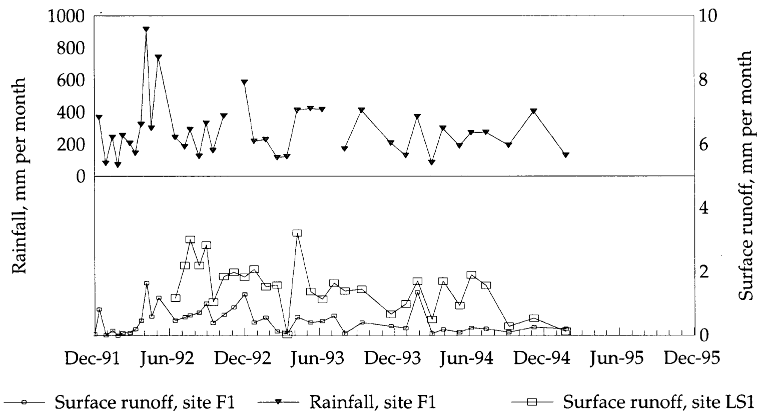

Figure 2. Rainfall and mean monthly surface runoff on forested hillslopes (site F1, 10 Gerlach troughs) and on a 1991 landslide scar with active vegetation regrowth (site LS1, 2 Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. Site F1 is in *Dacryodes* forest. Sites F1 and LS1 are underlain by Cretaceous tuffaceous sandstone and siltstone.

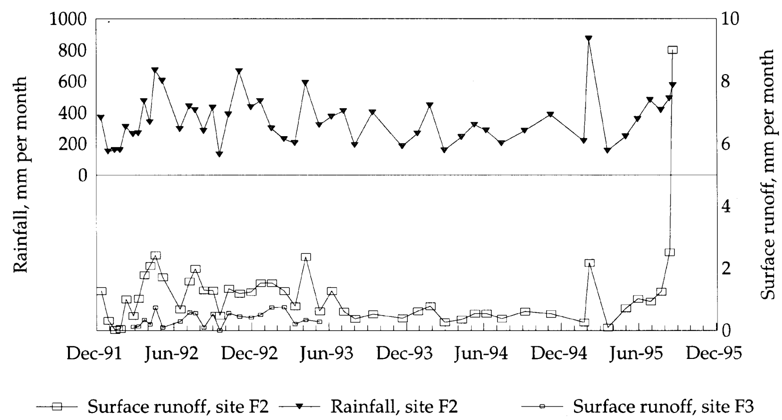

Figure 3. Rainfall and mean monthly surface runoff on forested hillslopes (sites F2, five Gerlach troughs and F3, two Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. Site F2 is in *Cyrilla* forest. Site F2 is in dwarf forest. Sites F2 and F3 are underlain by Tertiary quartz diorite

Ideally, Gerlach troughs should be sampled after each rainfall event so that each episode of slopewash can be related to rainfall of known duration and accumulation. For example, rainfall accumulation of 150 mm can result from multiple low-intensity showers or a single high-intensity storm. Much greater slopewash could be generated by the latter. The 27-day average sampling cycle resulted in the lumping of storms and slopewash so that specific effects of individual storms were not discriminated.

RESULTS AND DISCUSSION

Rainfall and surface runoff

Rainfall and surface runoff measured at the Gerlach trough sampling sites were not stationary during the 1992 to 1995 study period, declining each successive year (Figures 2,3 and 4, Tables II and III). Rainfall declined substantially from 1992 to 1994 – 17 per cent at the F1 site, where elevation is 220 m, and 24 per cent at the F2 site (elevation 650 m) (Tables II and III). At a NOAA rainfall station at Pico del Este, 1051 m elevation, rainfall declined by 29 per cent during this same period (Figure 1, Table II).

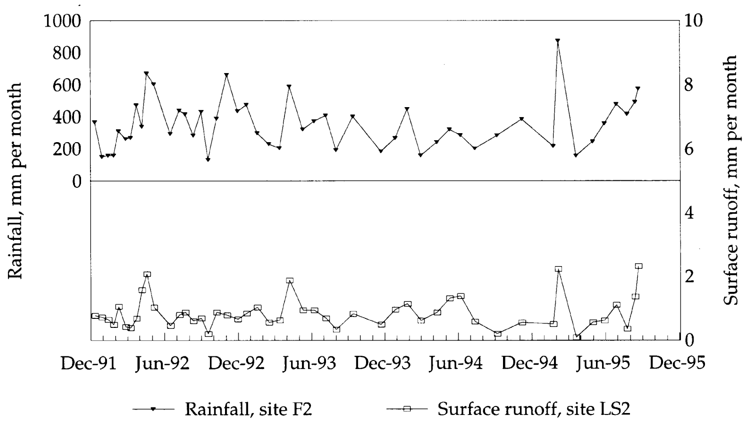

Figure 4. Rainfall and mean monthly surface runoff on a 1989 landslide scar with active vegetation regrowth (site LS2, two Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. Site F2 is in *Cyrilla* forest. Sites F2 and LS2 are underlain by Tertiary quartz diorite

Table II. Annual rainfall measured at a NOAA weather station and Gerlach trough sampling sites in the Luquillo Experimental Forest, Puerto Rico. NOAA rainfall data are from the Pico del Este station 666992, elevation 1051 m (data from US Department of Commerce, 1993 to 1996). See Figure 1 for site locations

	Annual rainfall (mm)		
Year	NOAA	Site F1	Site F2
1992	4919	3506	4447
1993	3936	2966	3726
1994	3476	2895	3380
1995*	3583	–	3110
Mean	3979	3122	3666

*Sampling ended in December 1994 at the F1 site and September 1995 at the F2 site

Table III. Annual surface runoff measured at Gerlach trough sampling sites in the Luquillo Experimental Forest, Puerto Rico. See Figure 1 for site locations. Site F1 is in *Cyrilla* forest. Sites F1 and LS1 are underlain by Cretaceous tuffaceous sandstone and siltstone and sites F2 and LS2 are underlain by Tertiary quartz diorite

	Annual surface runoff (mm)							
	Site F1		Site F2		Site LS1		Site LS2	
Year	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1992	7·2	0·7	14·0	1·5	24·2	7·4	9·6	4·9
1993	4·4	0·5	12·3	1·8	17·6	9·1	10·1	4·7
1994	3·7	0·4	6·2	1·0	13·6	6·8	10·3	4·4
1995*	–	–	24·0	3·1	–	–	12·3	9·1
Mean for study	5·1	5·0	14·1	1·9	18·5	7·8	10·6	5·8

*Sampling ended in December 1994 at the F1 and LS1 sites and September 1995 at the F2 and LS2 sites. Mean and standard deviation (SD) calculated from annual totals of 10 Gerlach troughs at site F1, five Gerlach troughs at site F2, and two Gerlach troughs each at sites LS1 and LS2

Because sampling at the F2 and LS2 sites was discontinued in September 1995, the 1995 annual rainfall total shown in Table II does not represent the entire year. The passage of Hurricanes Luis and Marilyn in September 1995 accounts for the upturn in rainfall and surface runoff at the very end of the sampling period at the F2 and LS2 sites (Figures 3 and 4). The drying trend during the period 1992 to 1995 was an island-wide phenomenon (US Department of Commerce, 1993, 1994, 1995, 1996).

Annual surface runoff measured with Gerlach troughs was less than 1 per cent of annual rainfall (Tables II and III). These data are in general agreement with those of Jordan (1970) who collected 1·75 to 3·25 per cent of water applied to experimental plots designed to measure surface runoff at the litter layer in the LEF. Below the root and litter layer, at a depth of 30 cm, runoff accounted for 20 to 52 per cent of the water applied to the plot surface (Jordan, 1970). Immediately beneath and within the litter layer are abundant fine to coarse roots and an extensive network of macropores created by the roots and worm burrows. Earthworms number approximately 190 per square metre in secondary forests near the study area (González *et al.*, 1996; Zou and González, 1997) and are estimated to range from 150 to 300 per square metre in colorado forest, where sites F2 and LS2 are located (X. Zou, University of Puerto Rico, oral communication, 1997). This combination of floral and mesofaunal factors at the soil surface makes for an environment with rare surface runoff but abundant near-surface throughflow.

Surface runoff is dependent, among various factors, on the rate at which rainfall infiltrates a soil surface. Highly variable infiltration rates were noted for small (1 to 2 m^2) contiguous patches of soil in the study areas. On a gently sloping ridgetop near the F2 site, bare soil with few roots present at the surface had an infiltration rate, determined with a single test, of 0.0010 cm s^{-1} (Stonestrom *et al.,* 1998). At the same time and location, 132 cm away, soil with abundant roots and leaf litter at the surface had an infiltration rate of 0·46 cm s^{-1} (three tests; standard deviation of 0·02), a 500-fold difference. These infiltration rates are equivalent to 36 to 17000 mm h^{-1} (even the low value exceeds all but the most extreme rainfall intensities) and explain the very low surface runoff rates observed in this study.

Annual surface runoff measured at a 1991 landslide scar (site LS1) was higher than that measured in the adjacent tabonuco forest (site F1) throughout the study period (Table III, Figure 2). The landslide slip surface exposed a weathered saprolite layer that appeared to have relatively low permeability, compared to that observed under the forest canopy. The saprolite exposed on the slip surface was smooth, fine textured, had no visible macropores, and had a dry bulk density of 1·3 g cm^{-3} in contrast to a mean dry bulk density of 0·75 g cm^{-3} at the forested (F1) sites (Table I). The 1989 landslide scar monitored at site LS2 was two years old at the onset of the study and vegetation regrowth upslope of the Gerlach troughs was substantial during the study period. Annual surface runoff measured at the LS2 landslide scar and under nearby colorado forest canopy at the F2 site was, on average, about the same, at 11 to 14 mm. Annual surface runoff at the F3 site, in dwarf forest, was only 3 mm. Dwarf forest occurs in the wettest, highest-elevation areas of the LEF. Thick layers (5 to 10 cm) of leaf litter and extremely porous root mats overlie the soil and create an extensive network of voids and macropores. Surface runoff is rarely observed.

Correlation between monthly surface runoff and monthly rainfall using simple least-squares linear regression models was better than expected considering the uncertainties of and spatially variable surface runoff catchment area for each Gerlach trough (Figures 5 and 6). The coefficient of determination (r^2) was only 0·30 for data collected at the F2 site but was 0·62 at the F1 site. However, the higher coefficient of determination at the F1 site is strongly controlled by the three highest data points. Without these, the coefficient of determination is 0·31. The slope for the correlation between monthly surface runoff and monthly rainfall at the F1 and F2 sites ranged from 0·0018 to 0·0046, meaning that monthly surface runoff was only 0·2 to 0·5 per cent of monthly rainfall. Model confidence limits were 95 per cent, as was the case with the other least-squares linear regression models discussed below.

Slopewash

Time series of slopewash and rainfall data measurements on forested hillslopes show consistent qualitative agreement through the study period (Figures 7 and 8). At all sampling sites, slopewash

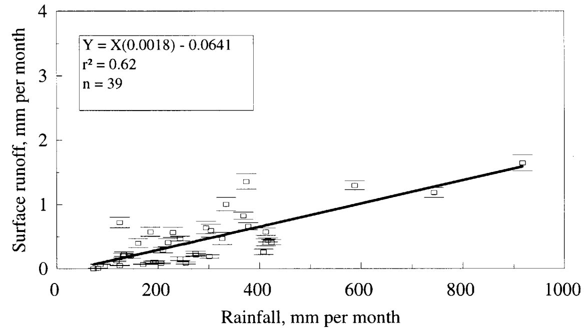

Figure 5. Relation between monthly rainfall and mean surface runoff collected on hillslopes in *Dacryodes* forest overlying Cretaceous tuffaceous sandstone and siltstone (site F1, 10 Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. High-low bars are at one standard deviation

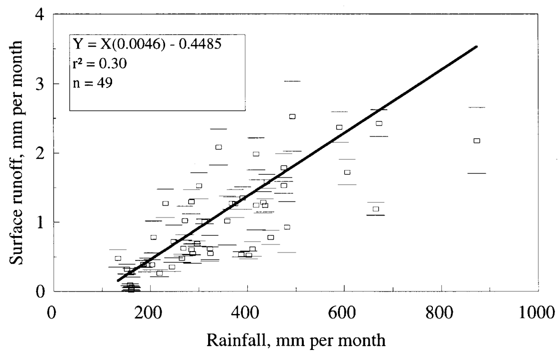

Figure 6. Relation between monthly rainfall and mean monthly surface runoff collected on hillslopes in *Cyrilla* forest overlying Tertiary quartz diorite (site F2, five Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. High–low bars are at one standard deviation

increased during periods of high rainfall and decreased during periods of diminished rainfall. The magnitude of slopewash varied with each combination of bedrock and forest type (Table IV). Slopewash was highest at the F2 site, lowest at the F3 site, and intermediate at the F1 site. Very low annual rates of erosion were observed at the dwarf forest site (F3) as expected because of the character of the soil surface in that environment.

Monthly slopewash was higher on the sandy loam soils associated with quartz diorite bedrock at the F2 site and lower on the silty clay loam soils associated with tuffaceous sandstone and siltstone at the F1 site (Figures 7 and 8). Soils at the F2 site have a higher sand per centage and lower clay per centage than those developed from the tuffaceous sandstone and siltstone parent material at the F1 site (Table I). This results, in part, from the high quartz content of the soil weathered from intrusive bedrock. Annual slopewash at the F1 site was 9 g m^{-2}, compared to 46 g m^{-2} at the F2 site (Table IV). In contrast, erosion measured on soil developed from quartz diorite in dwarf forest (F3) was only 2 g m^{-2} a^{-1}. Annual erosion measured on two landslide scars in 1992 ranged from 100 to 349 g m^{-2} but decreased to only 3 to 4 g m^{-2} by 1995.

Time series of slopewash and rainfall measured at the two landslide scars indicate a marked decrease in slopewash through time, particularly at the LS1 site (Figures 7 and 8). By the end of the study, in 1995, slopewash rates on both landslide scars were lower than rates under forest canopy, suggesting that the hydrologic and biologic characteristics of the scar soil surface are substantially altered, compared to

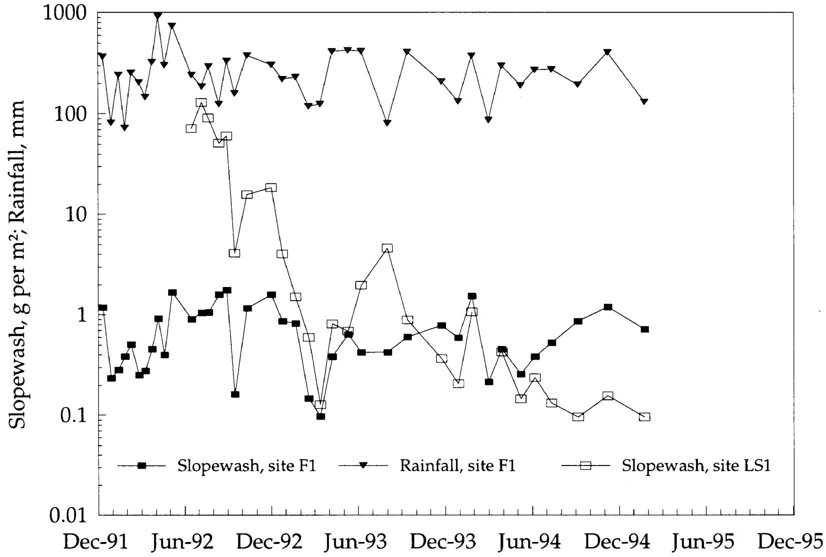

Figure 7. Rainfall and mean monthly slopewash on forested hillslopes (site F1, 10 Gerlach troughs) and on a 1991 landslide scar with active vegetation regrowth (site LS1, two Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. Site F1 is in *Dacryodes* forest. Sites F1 and LS1 are underlain by Cretaceous tuffaceous sandstone and siltstone

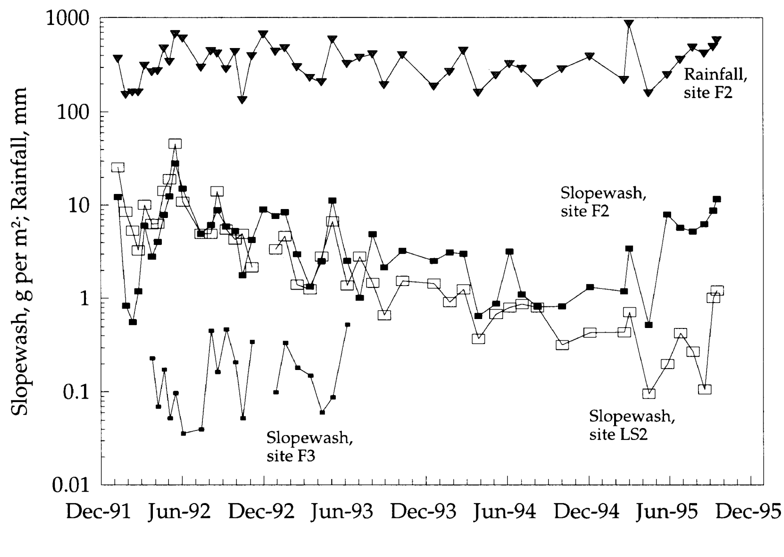

Figure 8. Rainfall and mean monthly slopewash on forested hillslopes (site F2, 5 Gerlach troughs; site F3, two Gerlach troughs) and on a 1989 landslide scar with active vegetation regrowth (site LS2, two Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. Site F2 is in *Cyrilla* forest. Site F3 is in dwarf forest. Sites F2, F3 and LS2 are underlain by Tertiary quartz diorite

Table IV. Annual slopewash measured at Gerlach trough sampling sites in the Luquillo Experimental Forest, Puerto Rico. See Figure 1 for site locations. Site F1 is in *Dacryodes* forest and site F2 is in *Cyrilla* forest. Sites F1 and LS1 are underlain by Cretaceous tuffaceous sandstone and siltstone and sites F2 and LS2 are underlain by Tertiary quartz diorite

	Annual slopewash ($g\,m^{-2}$)							
	Site F1		Site F2		Site LS1		Site LS2	
Year	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1992	11·2	8·0	80·4	61·3	349·2	17·5	99·5	1·4
1993	7·3	5·5	44·6	37·9	18·7	3·0	25·3	1·4
1994	8·0	4·7	18·2	15·5	2·7	0·0	7·6	4·0
1995*	–	–	41·1	20·7	–	–	3·5	1·1
Mean for study	8·8	6·1	46·1	33·8	123·5	6·9	34·6	2·0

*Sampling ended in December 1994 at the F1 and LS1 sites and September 1995 at the F2 and LS2 sites. Mean and standard deviation (SD) calculated from annual totals of 10 Gerlach troughs at site F1, five Gerlach troughs at site F2, and two Gerlach troughs each at sites LS1 and LS2

soil characteristics beneath nearby closed-canopy forest. The saprolite exposed on the surfaces of the landslide scars had a greater density and lower porosity compared to that of the soils beneath forest canopy (Table I). In addition, a pervasive black epiphyll crust developed on the landslide scar surfaces, composed of mosses and blue-green algae. Among the blue-green algae present in the LEF are *Nostoc, Scytonema, Anabaena* and *Calothrix* (Edmisten, 1970). The crust and the low-porosity saprolite surface were observed to reduce the detachability of soil particles. Similar growth has been observed on landslide scars in Jamaica where a nitrogen-fixing lichen *Stereocaulon virgatum* constituted 79 per cent of the surface biomass on four 15-year old landslides (Dalling and Iremonger, 1994).

Monthly slopewash rates were initially higher on the LS1 landslide scar than on the LS2 landslide scar (Figures 7 and 8; Table IV). A key difference between the landslide scars was their age of exposure when sampling was initiated. The LS2 scar dates from 18 September, 1989 (Hurricane Hugo) and was several years old when sampling began. During the sampling period, vegetation, mainly climbing ferns (Gleicheniacea) and fast-growing trees that are common in canopy gaps, *Cecropia peltata*, *Cecropia schreberiana,* recolonized the bare soil. In contrast, the LS1 scar was only a few months old when sampling was initiated in 1992 and recolonization by vegetation was not as advanced during the study period. Slopewash rates on these scars appear to be strongly controlled by the state of vegetative recovery. These relatively small landslide scars were therefore enhanced sediment sources for several years following their initial occurrence.

Large landslide scars, 17 to 26 years old, have been observed to be active sediment sources for up to several decades because of gullying, periodic slumping of head and sidescarps, and subsequent exposure of fresh soil and saprolite (Larsen and Torres-Sánchez, 1996; 1998). Gullying of landslide scar surfaces may be an important mass-wasting process and source of fine sediment on recovering scars, but the magnitude of these processes was not evaluated in this study. The abundance and depth of gullies noted on landslide scars in the LEF and elsewhere in Puerto Rico is variable and does not seem to be consistently associated with scar age (Larsen and Torres-Sánchez, 1998). Field observations of fresh landslide scars were made immediately following the passage of Hurricane Hortense, 10 September, 1996. Rainfall in the LEF associated with the storm totalled 600 mm in a 24 h period (Torres-Sierra, 1997). All of the several dozen shallow landslides that were inspected in the LEF showed evidence of gullying, indicating that the landslides had been triggered early in the storm and that subsequent rainfall on the slipface had been sufficient to erode additional soil and saprolite from the scar surface.

The marked decrease in slopewash over time on landslide scars was an indisputable finding of this study (Figures 7 and 8; Tables II and IV). Could this simply be attributable to the decline in rainfall during the study period? This possibility was evaluated by calculating slopewash concentration,

Table V. Mean annual slopewash concentration measured at Gerlach trough sampling sites in the Luquillo Experimental Forest, Puerto Rico. Slopewash concentration is calculated as slopewash (in g m^{-2}) divided by runoff (in mm). See Figure 1 for site locations. Site F1 is in *Dacryodes* forest. Site F2 is in Cyrillo forest. Sites F1 and LS1 are underlain by Cretaceous tuffaceous sandstone and siltstone and sites F2 and LS2 are underlain by Tertiary quartz diorite

	Mean annual slopewash concentration (g m^{-2} mm^{-1})			
Year	Site F1	Site F2	Site LS1	Site LS2
1992	1·6	6·2	14·4	10·4
1993	1·7	3·8	1·1	2·5
1994	2·2	3·2	0·2	0·7
1995*	–	1·7	–	0·3
Mean	1·8	3·7	5·2	3·5

*Sampling ended in December 1994 at the F1 and LS1 sites and September 1995 at the F2 and LS2 sites. Data calculated from annual totals of 10 Gerlach troughs at site F1, five Gerlach troughs at site F2, and two Gerlach troughs each at sites LS1 and LS2

expressed as slopewash divided by surface runoff (Table V). Slopewash concentration measured on the two landslide scars decreased by a factor of 35 on the landslide scar at site LS2 and by more than 70 on the landslide scar at site LS1 (Table V). In contrast, on the forested hillslopes, slopewash concentration decreased only by a factor of four at the F2 forest site and increased slightly at the F1 forest site.

The increase in slopewash concentration at the F1 site, in spite of decreasing surface runoff, raises another question. The increase is thought to have resulted from the gradual thinning of understorey vegetation and closure of the forest canopy that followed the extreme canopy damage caused by Hurricane Hugo in the northeastern sections of the LEF (Scatena and Larsen, 1991; Walker *et al*., 1991). Although not measured in this study, rainsplash originating as canopy drip causes an impact that is an important physical mechanism for initiation of soil particle transport in comparable tropical forests in southeast Asia (Douglas, 1967, 1968). Rainfall composed of relatively small droplets is concentrated by canopy interception, followed by the drainage of individual leaves via drip tips. Drip tips (elongated ends) are a physiological adaptation of trees in rain forest environments that facilitate rapid shedding of water thereby enhancing transpiration (Williamson, 1983). During the study period, three changes in forest structure occurred that would intensify canopy drip: the canopy changed from relatively open to relatively closed; the height of the canopy over the forest floor increased as seedlings and saplings (mainly the fast-growing gap invader *Cecropia*) were recruited; and the herbaceous understorey was suppressed because of increasing shade.

Correlation between monthly slopewash and rainfall using simple least-squares linear regression models was comparable to that discussed above for surface runoff and rainfall (Figures 9 and 10). The coefficient of determination (r^2) was 0·40 for data collected at the F2 site and 0·51 at the F1 site. The regression slope was seven times greater in the F2 site model compared to that of the F1 model, indicating, as discussed above, that the sandier soils developed over intrusive bedrock are far more easily eroded than the more cohesive soils derived from the tuffaceous sandstone and siltstone.

Bioturbation by soil mesofauna controls important micro- to meso-scale geomorphic, physical and chemical soil characteristics such as soil permeability and nutrient status, among others (Ellis and Mellor, 1995). Charles Darwin was among the first to quantify the amount of geomorphic work performed by earthworms. Using data from a field in Staffordshire, England, he estimated that earthworms annually bring up to the soil surface dry earth weighing 1·7 kg m^{-2} (Darwin, 1881, cited in Bates and Humphrey, 1956). As noted previously, earthworms are abundant in LEF soils. Although not quantified, a common field observation at the Gerlach trough sites were small (0·5 to 1 cm^3), roughly spherical clasts of worm castings extruded to the soil surface. The silty clay clasts were easily detached

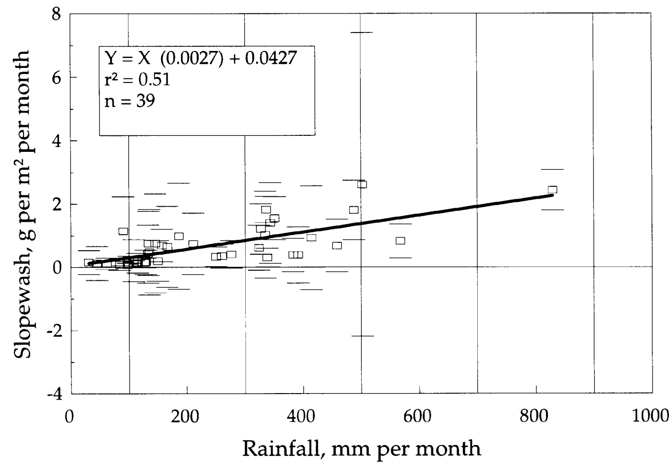

Figure 9. Relation between monthly rainfall and mean monthly slopewash on hillslopes in *Dacryodes* forest overlying Cretaceous tuffaceous sandstone and siltstone (site F1, 10 Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. High–low bars are at one standard deviation

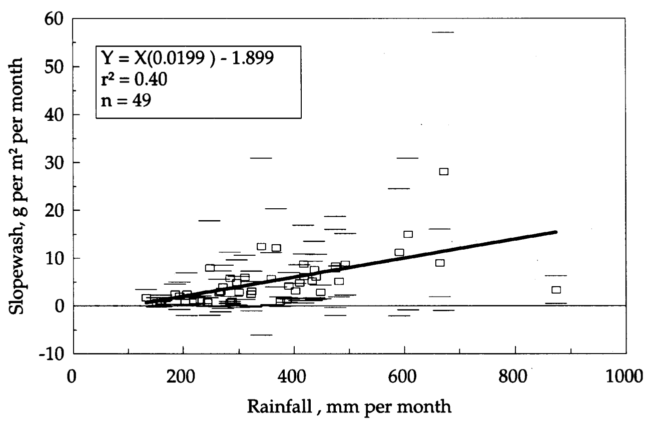

Figure 10. Relation between monthly rainfall and mean monthly slopewash on hillslopes in *Cyrilla* forest overlying Tertiary quartz diorite (site F2, five Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. High–low bars are at one standard deviation

and would roll downslope into Gerlach troughs. Because they disintegrated upon rewetting, the number or mass of clasts in the troughs could not be assessed during sampling. This raises a question regarding the operational definition of LOI as fine-litter transport. There are three groups of earthworms – those that feed on soil, decomposed fine litter, or both. Soil feeders are the dominant species in the LEF (Xiaoming Zou, University of Puerto Rico, written communication, 1997). It can be assumed that earthworms pass essentially all of the mineral soil and eliminate no more of the mass of decomposed fine litter than they take in so even if their casts were a significant portion of the material trapped by the Gerlach troughs, LOI would still be mainly fine litter, albeit somewhat processed by worms. The clast abundance indicates that bioturbation merits further study as the mass and composition of worm castings may be an important component of slopewash in these watersheds.

Table VI. Annual fine litterfall measured at Gerlach trough sampling sites in the Luquillo Experimental Forest, Puerto Rico. See Figure 1 for site locations. Site F1 is in *Dacryodes* forest and site F2 is in *Cyrilla* forest. Sites F1 abd LS1 are underlain by Cretaceous tuffaceous sandstone and siltstone and sites F2 and LS2 are underlain by Tertiary quartz diorite

	Annual litter transport ($g\,m^{-2}$)							
	Site F1		Site F2		Site LS1		Site LS2	
Year	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1992	607	321	562	276	32	na	48	na
1993	595	453	533	173	60	na	64	na
1994	608	225	1418	1542	110	na	63	na
1995*	–	–	1159	202	–	–	77	na
Mean for study	603	333	918	548	67	na	63	na

*Sampling ended in December 1994 at the F1 and LS1 sites and September 1995 at the F2 and LS2 sites. Mean, total and standard deviation (SD) calculated from annual totals of 10 litter traps at site F1, four litter traps at site F2, one litter trap each at sites LS1 and LS2; na = not applicable

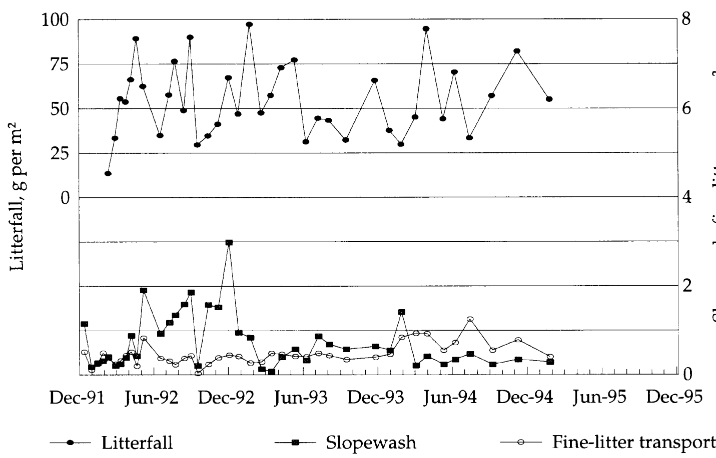

Figure 11. Mean monthly litterfall, slopewash and fine-litter transport on forested hillslopes in *Dacryodes* forest overlying Cretaceous tuffaceous sandstone and siltstone (site F1, 10 Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995

Fine litterfall and transport of fine litter

Mean annual litterfall at the forested study sites ranged from 603 to 918 g m^{-2} a^{-1} and is in general agreement with published values of 869 g m^{-2} a^{-1} (Scatena *et al.,* 1996) and 876 g m^{-2} a^{-1} (Lodge *et al.*, 1991) for subtropical wet forest (Table VI, Figures 11 and 12). Annual fine-litter transport, operationally defined as the LOI portion of slopewash, was 5 to 8 g m^{-2} at the two forested study sites from 1992 to 1995 (Table VII, Figures 13 and 14). This represents about 1 per cent of mean annual litterfall at each of the two forested sites. Very low leaf-litter transport rates are expected in humid tropical forests because of rapid litter decomposition, litter exploitation by mesofauna, and the anchoring effect of fine roots that commonly penetrate into the litter layer (Lodge *et al.*, 1991; Zou and González, 1997). Furthermore, humid tropical forests are known to be efficient recyclers of nutrients and are not likely to lose much fine litter to normal transport processes (Lugo and Scatena, 1995).

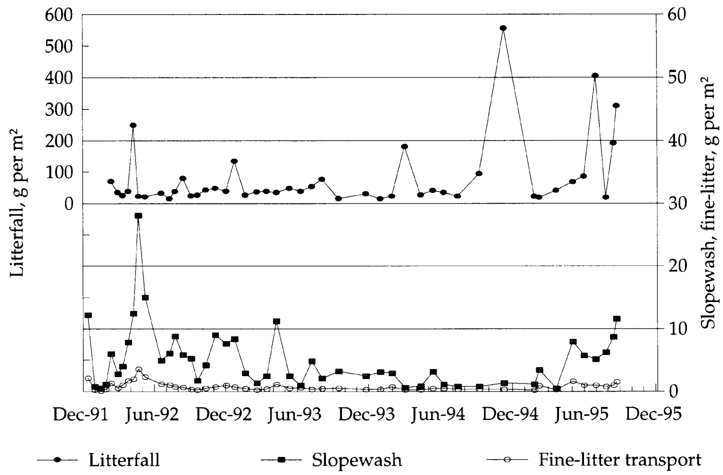

Figure 12. Mean monthly litterfall, slopewash and fine-litter transport on forested hillslopes in *Cyrilla* forest overlying Tertiary quartz diorite (site F2, five Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995

Table VII. Annual fine litter transport measured at Gerlach trough sampling sites in the Luquillo Experimental Forest, Puerto Rico. Fine litter transport determined as loss on ignition portion of slopewash samples. See Figure 1 for site locations. Site F1 is in *Dacryodes* forest and site F2 is in *Cyrilla* forest. Sites F1 and LS1 are underlain by Cretaceous tuffaceous sandstone and siltstone and sites F2 and LS2 are underlain by Tertiary quartz diorite

	Annual fine litter transport ($g\,m^{-2}$)							
	Site F1		Site F2		Site LS1		Site LS2	
Year	Mean	SD	Mean	SD	Mean	SD	Mean	SD
1992	4·2	3·3	13·3	11·2	nd	na	5·3	0·1
1993	4·1	4·0	6·2	4·3	2·8	0·1	2·2	0·1
1994	7·2	5·6	4·3	2·6	1·8	0·4	1·1	0·0
1995*	–	–	8·5	5·9	–	–	1·4	0·1
Mean for study	5·2	4·3	8·1	6·0	2·4	0·3	2·5	0·1

*Sampling ended in December 1994 at the F1 and LS1 sites and September 1995 at the F2 and LS2 sites. Mean and standard deviation (SD) calculated from annual totals of 10 litter troughs at site F1, five Gerlach troughs at site F2, and two Gerlach troughs each at sites LS1 and LS2; na = not applicable; nd = no data

Mean annual fine-litter transport was 18 per cent of slopewash at the colorado (F2) sites during the study (Table VII). In contrast, mean annual fine-litter transport at the tabonuco (F1) sites (where lower rates of slopewash prevail) was 59 per cent of slopewash. As expected, mean annual fine-litter transport on the two landslide scars was minimal, at $< 3\,g\,m^{-2}$, representing 2 to 7 per cent of the mean annual slopewash (Table VII). Time series plots shows that fine-litter transport varied closely with slopewash at the Gerlach though sampling sites (F2) in the colorado forest (Figure 12). At those sites, a least-squares linear regression model of monthly fine-litter transport on monthly slopewash had a coefficient of determination (r^2) of 0·84 (Figure 14); however, at the tabonuco (F1) sites, fine-litter transport increased during the study while slopewash decreased (Figure 11). This lack of stationarity resulted in poor agreement between monthly fine-litter transport and slopewash at the F1 site (Figure 13). Good correlation was not expected at the tabonuco (F1) sites because of the recent history of extreme disturbance of the forest canopy. The increasing trend in fine-litter transport corresponds to the general

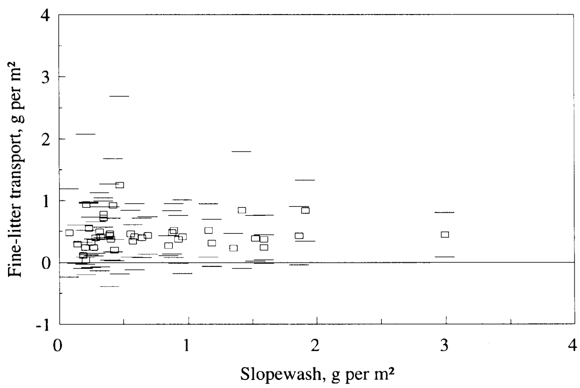

Figure 13. Relation between mean monthly slopewash and fine-litter transport on hillslopes in *Dacryodes* forest, overlying Cretaceous tuffaceous sandstone and siltstone (site F1, 10 Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. High–low bars are at one standard deviation

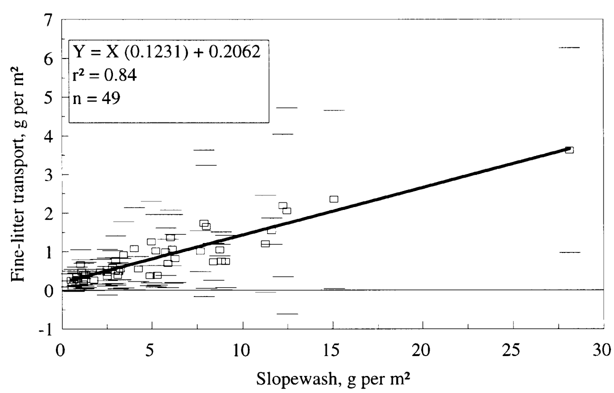

Figure 14. Relation between mean monthly slopewash and fine-litter transport on hillslopes in *Cyrilla* forest overlying Tertiary quartz diorite (site F2, five Gerlach troughs), Luquillo Experimental Forest, Puerto Rico, 1992 to 1995. High–low bars are at one standard deviation

increase in above-ground biomass that has occurred since Hurricane Hugo reduced above-ground biomass by 50 per cent in 1989 (Scatena *et al*., 1996). During the five years following the hurricane, mean daily total litterfall recovered to 83 per cent of pre-disturbance values. The hurricane caused extensive canopy damage at the F1 site but had relatively little effect at the F2 and F3 sites (Walker *et al*., 1991).

CONCLUSIONS

Understanding the mechanisms and the rates by which land surfaces are altered by natural and human geomorphic agents is a central focus of geomorphological research and a fundamental requirement of effective management of natural resources. In environments such as the tropics that have undergone or are undergoing rapid land surface alteration for agriculture, construction or logging, geomorphologic information enables land managers to attempt to mitigate landscape degradation. Surface runoff and slopewash are basic geomorphic processes that affect hillslope and catchment-scale hydrology, surface

water sediment concentration and chemistry, aquatic habitats, etc. Quantification of these and other geomorphic variables in the LEF provides the opportunity to examine them in a vulnerable landscape type – the humid tropics.

Surface runoff measured above the litter layer was almost non-existent at sites overlying the two principal bedrock types in the LEF. A highly porous root and litter horizon of up to 10 cm thickness, with numerous macropores created by earthworms and roots, allows for extremely rapid infiltration of rainfall. Monthly surface runoff on these very steep hillslopes correlated reasonably well with monthly precipitation and, on average, was only 0·2 to 0·5 per cent of rainfall.

Monthly slopewash (the erosion of soil particles) also correlated well with monthly rainfall. Slopewash was higher, averaging 46 g m^{-2} a^{-1} in sandy loam soils (where parent material is quartz diorite) than in silty clay loam soils derived from tuffaceous sandstone and siltstone where the average was 9 g m^{-2} a^{-1}. These slopewash rates are comparable to rates measured elsewhere in the tropics, although data from forested environments are few. To erode 1 g of soil per square metre on steep hillslopes in the LEF, the sites on tuffaceous sandstone and siltstone required monthly rainfall of 300 to 400 mm, but only 100 to 200 mm of rainfall was necessary to do the same amount of geomorphic work at the sites overlying quartz diorite. The difference may be explained by the lower cohesion of soils derived from quartz diorite. These soils, with median cohesive strength of 5·37 kPa, are composed of 16 per cent clay whereas soils derived from tuffaceous sandstone and siltstone have 42 per cent clay and median cohesive strength of 7·79 kPa. In addition, the study hillslopes overlying quartz diorite bedrock were, on average, steeper (at 41°) than those sampled on tuffaceous sandstone and siltstone, where mean slope angle was 35°. Steeper hillslopes would be expected to yield more slopewash per unit rainfall.

Fresh landslide scar surfaces yielded annual slopewash of 100 to 349 g m^{-2} but these rates decreased substantially with the age of the scar. During the four-year study period, slopewash on landslide scars decreased to only 3 to 4 g m^{-2} a^{-1}, a value less than that measured on the nearby forested hillslopes. For a fresh landslide scar, the slopewash rate is equivalent to two to 40 times the mean annual slopewash rate for undisturbed forest, attesting to the apparent importance of landslide scars as localized sediment sources. However, the mass of material that is displaced downslope during the initial episode of landsliding is the principal component of mass-wasting, and ranges from 480 to 700 Mg km^{-2} a^{-1} in the LEF (Larsen, 1997). The surface area exposed by landsliding ranges from 80 to 260 m^2 km^{-2} a^{-1}. Using the annual slopewash rate of 100 to 349 g m^{-2} for fresh landslide scars, this translates to only 8 to 91 kg km^{-2} a^{-1} of annual colluvial sediment production during the first few years after landslide occurrence. According to these estimates, slopewash that occurs after the original landslide occurrence moves a negligible amount of additional sediment downslope.

Slopewash rates on landslide scars seems to be strongly controlled by the state of vegetative and soil recovery. Field observations of recent landslide scars and the slopewash data collected in this study indicate that the hydrologic and biologic characteristics of a landslide scar soil surface are substantially altered, compared to soil characteristics beneath intact forest. The dense, smooth saprolite exposed on the surfaces of landslide scars provides a substrate upon which epiphyllae develop extensive mats of blue-green algae and mosses. The mats effectively seal the soil surface and reduce the tendency for rainsplash to detach soil particles. As the surface is revegetated by seedling recruitment and encroachment along the perimeter of the landslide scar, penetration by roots and soil mesofauna gradually returns the soil surface to the conditions observed under forest canopy. A period of 40 to 55 years may be required before slopewash rates return to the rates observed under forest canopy. Soil organic material in the upper 10 cm of landslide scars recovers to pre-disturbance levels in 40 to 55 years according to data developed from a chronosequence of 12 landslide scars in the LEF (Zarin and Johnson, 1995). A study of 46 landslides mapped at elevations of 530 to 850 m in the LEF indicated that basal area, plant biomass and floristic composition start to resemble pre-disturbance conditions after 50 years (Guariguata, 1990). The local-scale landslide disturbance cycle may be reset by hurricanes just as soil conditions have returned to pre-disturbance status (Scatena, 1995). A principal mechanism for

triggering of landslides in the LEF are hurricanes, which, as noted above, have directly crossed the LEF about once every 60 years during the past several hundred years (Scatena and Larsen, 1991).

The mean annual mass of fine litter (mainly leaves and twigs) transported downslope, measured using Gerlach troughs, ranged from 5 to 8 g m^{-2} and was lower at the tabonuco forest (tuffaceous sandstone and siltstone bedrock) site, where post-Hurricane Hugo recovery is still in progress. Monthly fine-litter transport correlated very well with monthly slopewash at the colorado forest (quartz diorite bedrock) sites and on average was about 18 per cent of slopewash during the study period. Fine litter transported downslope amounted to about 1 per cent of mean annual litterfall at each of the two forested sites. Very low leaf-litter transport rates are expected in humid tropical forests because of rapid litter decomposition, litter exploitation by mesofauna, and the anchoring effect of fine roots that commonly penetrate into the litter layer.

How important is slopewash as a component of hillslope and fluvial sediment budgets? The direct contribution of mean annual slopewash to the fluvial sediment exported by rivers draining the LEF must be very small, as the quantity measured on the steep hillslopes described above represents only 5 per cent of the fluvial sediment yield from a watershed underlain by the quartz diorite bedrock (Larsen, 1995, 1997). Data from the 3·26 km Icacos watershed, within which sites F2, F3 and LS2 were located, permit an evaluation of the maximum contribution of slopewash to fluvial sediment yield (see Figure 1 for the location of the surface-water gauging station). Slopewash averaged across the watershed, where mean slope is 12°, should be less than the 46 g m^{-2} calculated during this investigation because only relatively steep hillslopes were studied. Mean annual fluvial sediment yield from the Icacos watershed during the period 1991 to 1995 was 954 Mg km^{-2}. Hillslope sources of sediment during the same period had an estimated total of 750 Mg km^{-2} a^{-1} and were partitioned into 700 Mg km^{-2} a^{-1} by landsliding, $\leqslant$46 Mg km^{-2} a^{-1} by slopewash, 19 Mg km^{-2} a^{-1} by treethrow, and 11 Mg km^{-2} a^{-1} by soil creep (Larsen, 1997). The 204 Mg km^{-2} difference between hillslope sources and fluvial export of sediment is presumably derived from unmeasured processes such as gullying of landslide scar surfaces, channel bank slumping, channel storage and, perhaps most importantly, the uncertainties of data measurement. Very little storage of colluvium is evident in LEF watersheds. They are upland catchments with abundant rainfall characterized by frequent high-magnitude storms and are not transport limited. Hillslope erosion is efficient at delivering sediment directly to channels or near-channel areas.

In summary, episodic landslide activity in the LEF calculated at decadal or greater time scales is far more important than any other form of mass-wasting with respect to the mass of earth materials moved downslope (Larsen, 1997). Nonetheless, the low-intensity, more continuous processes of slopewash (as well as soil creep and treethrow) provide a steady stream of sediment to fluvial systems sufficient to make up a substantial portion of fluvial sediment export during some years.

ACKNOWLEDGEMENTS

This work was funded through the US Geological Survey, Global Change, Water, Energy, and Biogeochemical Budgets (WEBB) Program (Larsen *et al*., 1993; Lins, 1994). Nel Caine, University of Colorado, merits special thanks because of his advice and suggestions for the dissertation from which these data were extracted. The manuscript benefited from reviews by Frederick N. Scatena, US Forest Service, and William J. Wolfe, US Geological Survey, and two anonymous reviewers. Thanks are owed to Wilfred Montaño and Hector Rivera for assistance in field data collection, and to Robert F. Stallard, William J. Wolfe, Allen C. Gellis, Richard M.T. Webb and Robert F. Fitzhugh, US Geological Survey, for assistance in study design and development of the Gerlach trough used in this investigation.

REFERENCES

ASTM, 1988. *Standard test method for infiltration rate of soils in field using double-ring infiltrometers,* American Society for Testing of Materials, Annual Book of ASTM Standards, D3385-88, 04..08, 407–412.

Bates, M. and Humphrey, P. S. (Eds) 1956. *The Darwin Reader*, Charles Scribner's Sons, New York, 470 pp.

Birot, P. 1968. *The Cycle of Erosion in Different Climates*, Batsford, London.

Birdsey, R. A. and Weaver, P. L. 1987. *Forest Area Trends in Puerto Rico*, US Department of Agriculture – Forest Service Research Note **SO-331**, 5 pp.
Boccheciamp, R. A. 1977. *Soil Survey of the Humacao Area of Eastern Puerto Rico*, US Department of Agriculture, Soil Conservation Service, 103 pp.
Briggs, R. P. and Aguilar-Cortés, E. 1980. *Geologic Map of the Fajardo and Cayo Icacos Quadrangles, Puerto Rico*, Miscellaneous Geologic Investigations Map **I-1153**, scale 1:20000, 1 sheet.
Brown, S., Lugo, A. E., Silander, S. and Liegel, L. 1983. *Research History and Opportunities in Luquillo Experimental Forest*, US Department of Agriculture, Forest Service, General Technical Report **SO-44**, 128 pp.
Bruenig, E. F. 1992. 'Tropical forest resources', in Furtado, J.I., Morgan, W.B., Pfafflin, J.R. and Ruddle, K. (Eds), *Tropical Resources – ecology and development*, Harwood Academic Publishers, Philadelphia, 67–96.
Cailleux, A. 1959. 'Études sur l'érosion et la sédimentation en Guyane', *Mém. Expl. Carte géol. de la France*, Dept. Guyane Française, Paris, 49–73.
Calvesbert, R. J. 1970. *Climate of Puerto Rico and the U.S. Virgin Islands*, US Department of Commerce, Climatography of the US, **60-52**, 29 pp.
Cerdà, A. and García-Fayos, P. 1997. 'The influence of slope angle on sediment, water and seed losses on badland landscapes', *Geomorphology*, **18** (2), 77–90.
Chatterjea, K. 1989. 'Surface wash – the dominant geomorphic process in the surviving rainforest of Singapore', *Singapore Journal of Tropical Geography*, **10**(2), 95–109.
Chatterjea, K. 1994. 'Dynamics of fluvial and slope processes in the changing geomorphic environment of Singapore', *Earth Surface Processes and Landforms*, **19**, 585–607.
Colón, J. A. 1983. 'Algunos aspectos de la climatologia de Puerto Rico', *Acta Cientifica,* **23**, 55–63.
Dalling, J. W. and Iremonger, S. 1994. 'Preliminary estimate of landslide disturbance in the Blue Mountains, Jamaica' *Caribbean Journal of Science*, **30**(3–4), 290-292.
Darwin, C. 1881. 'The formation of vegetable mould, through the action of worms, with observations on their habits', London, 8 vols, Ch. 24.
Donnelly, T. W. 1989. 'Geologic history of the Caribbean and Central America' in Bally, A. W., and Palemer A R. (Eds), *The Geology of North America – An Overview*, Geological Society of America, The Geology of North America, 299–321.
Douglas, I. 1967. 'Erosion of granite terrains under tropical rain forest in Australia, Malaysia, and Singapore', *International Union of Geodesy and Geophysics/International Association of Scientific Hydrology Symposium on River Morphology*, publication **75**, 31–39.
Douglas, I. 1968. 'Erosion in the Sungei Gombak catchment Selangor', *Journal of Tropical Geography*, **26**, 1–16.
Edmisten, J. 1970. 'Preliminary studies of the nitrogen budget of a tropical rain forest', in Odum, H. T. and Pigeon, R. F. (Eds), *A Tropical Rain Forest*, US Department of Commerce, National Technical Information Service, Springfield, Va, H211–H215.
Ellis, S. and Mellor, A. 1995. *Soils and Environment*, Routledge, London, 364 pp.
Ewel, J. J. and Whitmore, J. L. 1973. *The ecological life zones of Puerto Rico and the U.S. Virgin Islands*, US Department of Agriculture, Forestry Service Research Paper **ITF-18**, 72 pp.
Fitzhugh, R. 1992. 'Construction of simple surface runoff sampler', US Geological Survey, *Water Resources Division Instrument News*, **58**, 1-2.
Foth, H. D. 1984. *Fundamentals of Soil Science*, John Wiley and Sons, 435 pp.
García-Martino, A. R., Warner, G. S., Scatena, F. N. and Civco, D. L. 1996. 'Rainfall, runoff, and elevational relationships in the Luquillo mountains of Puerto Rico', *Caribbean Journal of Science*, **32**(4), 413–424.
Gellis, A. C., Webb, R. M. T., Wolfe, W. J. and McIntyre, S. C. I. (in press). *Effects of land use on upland erosion, sediment transport and reservoir sedimentation, Lago Loíza watershed, Puerto Rico*, US Geological Survey, Water Resources Investigation Report.
Gerlach, T. 1967. 'Hillslope troughs for measuring sediment movement', *Revue de Geomorphologie Dynamique, Special edition to the International Hydrological Decade*, **4**, 173.
González, G., Zou, X. and Borges, S. 1996. 'Earthworm abundance and species composition in abandoned tropical croplands: comparisons of tree plantations and secondary forests', *Pedobiologia*, **40**, 385–391.
Goudie, A. 1995. *The Changing Earth, Rates of Geomorphological Processes*, Blackwell Publishers, Oxford, 302 pp.
Guariguata, M. R. 1990. 'Landslide disturbance and forest regeneration in the upper Luquillo Mountains of Puerto Rico', *Journal of Ecology,* **78**, 814–832.
Jordan, C. F. 1970. 'Flow of soil water in the lower montane tropical rain forest', in Odum, H. T. and Pigeon, R. F. (Eds), *A Tropical Rain Forest*, National Technical Information Service, Springfield, VA. H201–H204.
Krynine, P. D. 1936. 'Geomorphology and sedimentation in the humid tropics', *American Journal of Science*, **32**, 297–306.
Lambe, T. W. 1951. *Soil Testing for Engineers*, John Wiley and Sons, New York, 165 pp.
Larsen, M. C. 1995. 'Comparison of sediment yields from forested and agriculturally-developed montane humid-tropical watersheds, Puerto Rico', (abstract) *International Association of Geomorphologists – Southeast Asia Conference*, Singapore, 18–23 June 1995.
Larsen, M. C. 1997. *Tropical geomorphology and geomorphic work: A study of geomorphic processes and sediment and water budgets in montane humid-tropical forested and developed watersheds, Puerto Rico*, PhD dissertation, University of Colorado, 341 pp.
Larsen, M. C. and Parks, J.E. 1997. 'How wide is a road? The association of roads and mass-wasting disturbance in a forested montane environment', *Earth Surface Processes and Landforms,* **22**(8), 835–848.
Larsen, M. C. and Torres-Sánchez, A. J. 1992. 'Landslides triggered by the rainfall associated with Hurricane Hugo, eastern Puerto Rico, September 1989', *Caribbean Journal of Science,* **28**(3–4), 113–120.
Larsen, M. C. and Simon, A. 1993. 'Rainfall-threshold conditions for landslides in a humid-tropical system, Puerto Rico' *Geografiska Annaler,* **75A**(1–2), 13–23.

Larsen, M. C., Collar, P. D. and Stallard, R. F. 1993. *Research plan for the investigation of water, energy, and biogeochemical budgets in the Luquillo mountains, Puerto Rico*, US Geological Survey Open-file Report **92–150**, 19 pp.

Larsen, M. C. and Torres-Sánchez, A. J. 1996. *Geographic relations of landslide distribution and assessment of landslide hazards in the Blanco, Cibuco, and Coamo river basins, Puerto Rico*, US Geological Survey Water Resources Investigations Report **95–4029**, 56 pp.

Larsen, M. C. and Concepción, I. M. 1998. 'Water budgets of small forested and agriculturally-developed montane watershed in eastern Puerto Rico' in Segarra-García, R.I. (Ed.) *Proceedings, Tropical Hydrology and Caribbean Water Resources*, American Water Resources Association, San Juan, Puerto Rico, 13–16 July 1998, 199–204.

Larsen, M. C. and Torres-Sánchez, A. J. 1998. 'The frequency and distribution of recent landslides in three montane tropical regions of Puerto Rico' *Geomorphology*, **24**(4), 309-331.

Lewis, L. A. 1981. 'The movement of soil materials during a rainy season in Western Nigeria', *Geoderma,* **25**, 13–25.

Lewis, L. A. 1985. 'Assessing soil loss in Kiambu and Murang'a districts, Kenya', *Geografiska Annaler,* **67A**(3–4), 273–284.

Lins, H. F. 1994. 'Recent directions taken in water, energy, and biogeochemical budgets research', *EOS, Transaction of the American Geophysical Union,* 75(38), 433–439.

Lodge, D. J., Scatena, F. N., Asbury, C. E. and Sánchez, M. J. 1991. 'Fine litterfall and related nutrient inputs resulting from Hurricane Hugo in subtropical wet and lower montane rain forests of Puerto Rico', *Biotropica,* **23**, 336–342.

Lugo, A. E. and Scatena, F. N. 1995. 'Ecosystem-level properties of the LEF with emphasis on the Tabonoco Forest', in Lugo, A. E. and Lowe, C. (Eds), *Tropical Forests: Management and Ecology*, Ecological Studies **112**, Springer-Verlag, 59–108.

Myster, R. W., Thomlinson, J. R. and Larsen, M. C. 1997. 'Predicting landslide vegetation using landscape characteristics of the Puerto Rican rain forest' *Landscape Ecology,* **12**, 299–307.

Odum, H. T., Drewry, G. and Kline, J. R. 1970. 'Climate at El Verde' in Odum, H. T. and Pigeon, R. F. (Eds), *A Tropical Rain Forest* US Department of Commerce, National Technical Information Service, Springfield, VA B347–B418.

Reading, A. J., Thompson, R. D. and Millington, A. C. 1995. *Humid Tropical Environments*, Blackwell, Cambridge, MA, 429 pp.

Ruxton, B.P. 1967. 'Slopewash under mature primary rainforest in northern Papua' in Jennings, J.N. and Mabbut, J.A. (Eds), *Landform Studies from Australia and New Guinea*, Cambridge University Press, Cambridge, 85–94.

Scatena, F. N. 1995. 'Relative scales of time and effectiveness of watershed processes in a tropical montane rain forest of Puerto Rico' in Costa, J.E., Miller, A.J., Potter, K.W., and Wilcock, P. R. (Eds), *Natural and Anthropogenic Influences in Fluvial Geomorphology*, American Geophysical Union, Geophysical Monograph **89**, 103–111.

Scatena, F. N. and Larsen, M. C. 1991. 'Physical aspects of Hurricane Hugo in Puerto Rico', *Biotropica,* 23(4A), 317–323.

Scatena, F. N. and Lugo, A. E. 1995. 'Geomorphology, disturbance, and the soil and vegetation of two subtropical wet steepland watersheds of Puerto Rico', *Geomorphology,* **13**, 199–213.

Scatena, F. N. Moya, S., Estrada, C. and Chinea, J. D. 1996. 'The first five years in the reorganization of aboveground biomass and nutrient use following Hurricane Hugo in the Bisley Experimental Watersheds, Luquillo Experimental Forest, Puerto Rico' *Biotropica,* **28**, 424–440.

Schumm, S. A. 1956, 'The role of creep and rainwash on the retreat of badland slopes', *American Journal of Science,* **254**, 693–706.

Seiders, V. M. 1971. *Geologic map of the El Yunque quadrangle, Puerto Rico*, U.S. Geological Survey Miscellaneous Geologic Investigations Map I-658, 1:20 000 scale, 1 sheet.

Simon, A., Larsen, M. C. and Hupp, C. R. 1990. 'The role of soil processes in determining mechanisms of slope failure and hillslope development in a humid-tropical forest: eastern Puerto Rico', in Kneuper, P. L. K. and McFadden, L. D. (Eds), *Soils and Landscape Evolution Geomorphology,* **3**, 263–286.

Sirvent, J., Desir, G., Gutierrez, M., Sancho, C. and Benito, G. 1997. 'Erosion rates in badland areas recorded by collectors, erosion pins and profilometer techniques (Ebro Basin, NE-Spain)' *Geomorphology,* **18**(2), 61–75.

Smith, R. M. and Abruña, R. 1955. *Soil and Water Conservation Research in Puerto Rico, 1938–1947*, University of Puerto Rico, Agricultural Experiment Station Bulletin **124**, 51 pp.

Stonestrom, D. A., White, A. F. and Akstin, K. C. 1998. 'Determining rates of chemical weathering in soils – solute transport versus profile evolution', *Journal of Hydrolog*y, **209**, 331–345.

Temple, P. H. and Rapp, A., 1972. 'Landslides in the Mgeta area, Western Uluguru Mountains, Tanzania', *Geografiska Annaler*, **54A**, 157–193.

Torres-Sierra, H. 1997. *Hurricane Hortense impact on surface water in Puerto Rico,* U.S. Geological Survey Fact Sheet **FS-014-97**, 4 pp.

Unesco/UNEP/FAO. 1978. *Tropical Forest Ecosystems*, Unesco, Paris.

US Department of Commerce. 1993. *Climatological Data, Annual Summary, 1992, Puerto Rico and Virgin Islands*, National Oceanic and Atmospheric Administration, **39**.

US Department of Commerce. 1994. *Climatological Data, Annual Summary, 1993, Puerto Rico and Virgin Islands*, National Oceanic and Atmospheric Administration, **40**.

US Department of Commerce. 1995. *Climatological Data, Annual Summary, 1994, Puerto Rico and Virgin Islands*, National Oceanic and Atmospheric Administration, **41**.

US Department of Commerce. 1996. *Climatological Data, Annual Summary, 1995, Puerto Rico and Virgin Islands*, National Oceanic and Atmospheric Administration, **42.**

Wadsworth, F. H. 1950. 'Notes on the climax forests of Puerto Rico and their destruction and conservation prior to 1900', *The Caribbean Forester,* **11**(1), 38-46.

Waide, R. B. and Lugo, A. E. 1992. 'A research perspective on disturbance and recovery of a tropical montane forest', in Goldammer, J.G. (Ed.), *Tropical Forests in Transition*, Berkhauser-Verlag, Basel, Switzerland, 173–190.

Walker, L. R., Lodge, D. J., Brokaw, N. V. L. and Waide, R. B. 1991. 'An introduction to hurricanes in the Caribbean' *Biotropica,* **23**(4), 313–316.

Walker, L. R., Zarin, D. J., Fetcher, N., Myster, R. W. and Johnson, A. H. 1996. 'Ecosystem development and plant succession on landslides in the Caribbean', *Biotropica,* **28**, 566–576.

Williams, M. A. J. 1973. 'The efficacy of creep and slopewash in tropical and temperate Australia', *Australian Geographical Studies,* 11, 62–78.

Williamson, G. B. 1983. 'Drip-tips, drop sizes and leaf drying', *Biotropica,* **15**, 232–234.

Young, A. 1960. 'Soil movement by denudational processes on slopes', *Nature,* **188**, 120–122.

Young, A. and Saunders, I. 1986. 'Rates of surface processes and denudation' in Abrahams, A. D. (Ed.), *Hillslope Processes*, Allen and Unwin, Boston, 1–27.

Zarin, D. J. and Johnson, A. H., 1995. 'Base saturation, nutrient cation, and organic matter increases during early pedogenesis on landslide scars in the Luquillo Experimental Forest, Puerto Rico', *Geoderma*, **65**, 317–330.

Zonneveld, J. I. S. 1975. 'Some problems of tropical geomorphology', *Zeitschrift für Geomorphologie N.F.,* **19**(4), 377–392.

Zou, X. and Gonzlez, G. 1997. 'Changes in earthworm density and community structure during secondary succession in abandoned tropical pastures', *Soil Biology and Biochemistry*., **29**(3/4), 627–29.

